Technical note

Revisiting alpha decay-based near-light-speed particle propulsion

Wenwu Zhang*, Zhen Liu, Yang Yang, Shiyu Du*

Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Zhejiang 315201, People's Republic of China

H I G H L I G H T S

- SRIM was used to study the alpha particle penetration depth and efficiency.
- Correlation between thickness of decayable foil and propulsion force was established.
- With the hypothesis of SAND, the travel time to Mars may be shortened to <20 days.

A R T I C L E I N F O

Keywords:
Near-light-speed particle propulsion
Monte Carlo simulation
Solar sail
Stimulated acceleration of nuclear decay

A B S T R A C T

Interplanet and interstellar travels require long-term propulsion of spacecrafts, whereas the conventional schemes of propulsion are limited by the velocity of the ejected mass. In this study, alpha particles released by nuclear decay are considered as a potential solution for long-time acceleration. The principle of near-light-speed particle propulsion (NcPP) was elucidated and the stopping and range of ions in matter (SRIM) was used to predict theoretical accelerations. The results show that NcPP by means of alpha decay is feasible for long-term spacecraft propulsion and posture adjustment in space. A practical NcPP sail can achieve a speed >150 km/s and reach the brink of the solar system faster than a mass equivalent solar sail. Finally, to significantly improve the NcPP sail, the hypothesis of stimulated acceleration of nuclear decay (SAND) was proposed, which may shorten the travel time to Mars to within 20 days.

1. Introduction

The fastest object artificially launched into space is NASA's New Horizons Spacecraft, which has a speed of approximately 16 km/s and had just passed Pluto after 9.5 years of voyage (Harwood, 2006). In general, the time required to travel to Mars is 6–9 months (Gravier et al., 1972). Having reached the moon, traveling Mars will be of interest in the coming years.

The conventional rocket-style propulsion cannot accelerate spacecraft to very high speed because of the limited velocity of the ejected mass. As an example, a powerful chemical fuel of a rocket is liquid H_2 and O_2, and the effective exhaust velocity of the reaction products is approximately 4.3 km/s. Because of the limited exhaust velocity, it is difficult to accelerate to high speed by a single-stage rocket (Sutton and Oscar, 2010). The plasma engine VASIMR by NASA (Cassady et al., 2010; Longmier et al., 2012) can emit particles at a speed of 50 km/s, which has been the fastest exhaust speed for engines currently. However, high voltage and large amount of energy are required, making it costly for interplanet exploration. Solar sails, which use light pressure from solar radiation, can produce long-time acceleration, which is decreased rapidly when it is far away from the Sun (Wright, 1992).

The alpha decay particles have an initial speed of approximately 0.05 c, where c is the speed of light in vacuum. The exhaust speed of the alpha particles is 300 times higher than that of plasma engines, and >3000 times higher than that of the chemical fuels of rockets. Let us define the particles with speed $>1/1000$ of the light speed as the near–light-speed particles (Nc-particles). Alpha decay particles, as typical Nc-particles, may be a potential solution for long-time acceleration in space.

The concept of using the Nc-particles, such as radioisotope decay particles, for space propulsion has been studied in the past decades (Berman, 1961; Bolonkin, 1982; Fiehler and Oleson, 2005; Bolonkin, 2005). The direct recoil propulsion is that some of the particles are emitted directly imparting kinetic energy to a spacecraft and maintaining the propulsion levels at distances from Sun compared with solar sail systems. The Nc-particles produce extremely high specific impulses, but generate very low thrust levels, not to mention in the desired direction, for a certain quantity of source. Many innovations have been proposed to decrease the weight of traditional sail, increase the thrust, and

* Corresponding authors.
E-mail addresses: zhangwenwu@nimte.ac.cn (W. Zhang), dushiyu@nimte.ac.cn (S. Du).

increase the propulsion efficiency by control thrust and thrust direction. Bolonkin (Bolonkin, 2005) decreased the weight of traditional sail for Nc-particles by two to four times and increased the thrust by three times. Kluever (Kluever, 1997) and Colombo (Colombo et al., 2009) used the appropriate optimal low-thrust trajectories based on differential dynamic programming to allow control of thrust and thrust direction. The near-light-speed particle propulsion (NcPP) method allows a space vehicle to reach > 200 km/s. Thus, it is a promising approach for long-term space traveling. However, the detailed study on the dependence of propulsion efficiency on different parameters of the designed devices has yet been performed. Hence, it is necessary to revisit space propulsion by the radioisotope decay particles, which may provide new clues for the application of decay particle propulsion in practice.

In this study, the Monte Carlo simulation was used to evaluate the efficiency of the alpha particle-generated kinetic energy and momentum and analyze the feasibility of direct alpha decay propulsion; the propulsion and final velocity of the spacecraft by alpha decay propulsion were calculated and compared with the results of solar sails. Finally, future improvements of this technology were discussed.

2. Principle of alpha decay-based propulsion

Alpha particles from natural decay are a common source of Nc-particles with energy in the range of 4–9 MeV. Because of their relatively large mass and two positive electric charges, alpha particles interact strongly with electrons and will stop within 100 μm in most condensed materials (Loveland et al., 2005). The thermal effect of nuclear decay has been utilized. The radioactive thermal generator (RTG) is currently the only human technology that enables extremely long-time supply of electricity for space probes (Bennett et al., 2008). Compact and neat nuclear decay-released kinetic energy is converted to thermal energy and then to electricity in an RTG unit. Using 8.1 kg of plutonium-238 with 83.5% purity, 4000-W thermal power and 220-W electricity will be available for a time span of > 20 years. Currently, there has been no replacement for RTG in deep space travel.

An interesting question is whether the kinetic energy of alpha particles from nuclear decay can be directly used to generate propulsion. The answer is yes, when omnidirectional radiation is achieved (Bolonkin, 1982). In general, a bulk decayable material will emit alpha particles in all directions with their momentums canceled out. However, if one side of the emission is shielded by an absorption layer, while the other side emits as usual, this could result in a net recoil force, as shown in Fig. 1. For natural decay, this force might be tinny, but can last a long time. In space, this force can be used for producing long-time acceleration, and eventually, a much higher speed of space travel than the current record can be reached. A key advantage is that nuclear decay can release Nc-particles without the requirement of additional energy.

3. Simulation of efficiency

In a bulk material, the Coulomb scattering with nucleus, which was used to estimate the diameter of atomic nucleus, can reveal the relationship between the scattering angle and the corresponding probability. For high-energy particles, the probability of high-angle scattering is rather small (Bethe, 1953). The stopping power of nuclear Coulomb scattering is much smaller than the scattering caused by electrons (Boschini et al., 2010); in other words, ionization is the main process for the energy loss of charged particles.

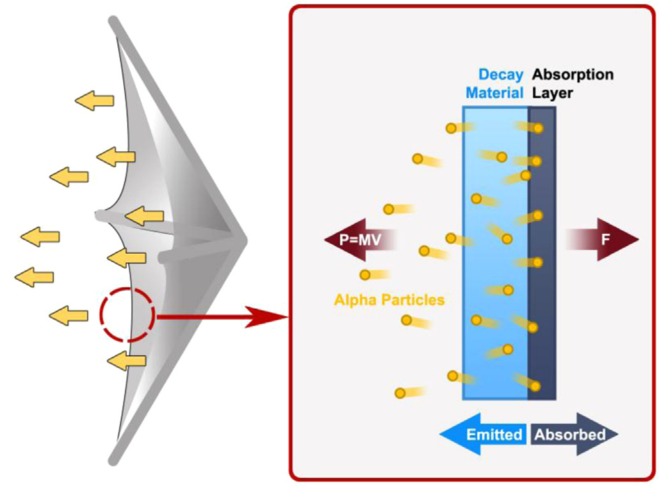

Fig. 1. Principle of the alpha-decay propulsion.

In order to predict the efficiency of emitting alpha particles, Monte Carlo simulation using SRIM codes (Ziegler et al., 2010) was adopted in this study, and the residual energy and penetration depth in a nuclear material were investigated. First, as a validation, penetration behaviors of 5-MeV alpha particles in gold were simulated and the results were compared with experimental observations (Comfort et al., 1966). The computational results are in excellent agreement with the measured ones (Fig. 2A). Second, similar schemes to predict the correlation between penetration depth and particle residual energy of alpha particles were used for the decayable materials, pure uranium, gold, and uranium dioxide.

It is obvious that only the momentum parallel to the forward direction is effective for propulsion, which can be termed as *effective momentum*. Thus, the effective momentum efficiency is defined as the ratio of the effective momentum to the overall momentum. Applying the modeling (see Supplementary Materials S1) and the simulation results from SRIM, the effective momentum efficiencies of 5-MeV alpha particle penetration as a function of foil thickness can be calculated, and are shown in Fig. 2B. The following several pieces of important information can be revealed:

(1) The efficiency decreases monotonically with increasing thickness. The upper bound of momentum efficiency is 1/4, so up to one-fourth of the initial momentum can contribute to propulsion in maximum.
(2) For elemental materials such as gold and uranium, the efficiency curves are very close to each other. This is because these materials possess metallic features in electronic structure and the free electrons can interact with alpha particles in a similar manner.
(3) For light elements, such as oxygen in uranium dioxide, the ability of stopping alpha particles is much lower, and hence the efficiency of uranium dioxide is higher than those of heavy metals. However, considering that the atomic densities of decayable elements in dioxide materials are much lower than pure metal, the propulsion ability of dioxides may be lower than that of pure metals.
(4) The effective momentum efficiency can be estimated by

$$\eta_{P,L} = \frac{\eta_{P,0}(L_i - L)}{L_i} = \frac{(L_i - L)}{4L_i}, \tag{1}$$

where L_i is the intercept on the thickness axis of the linear fitting curve (Fig. 2B) and $\eta_{P,0}$ is the efficiency when thickness=0, which

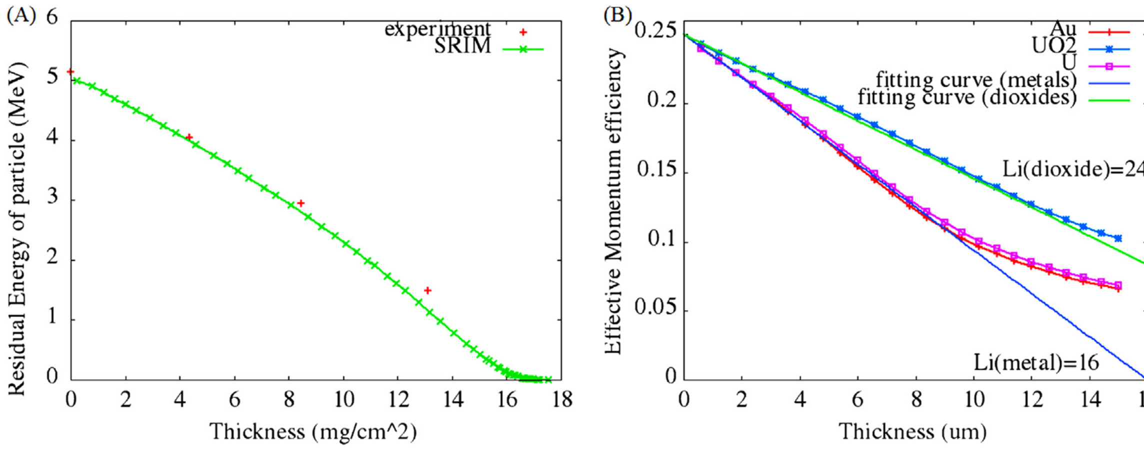

Fig. 2. (A) The residual energy as a function of penetration thickness in gold from SRIM simulation (green x) and experiment (red +); (B) The effective momentum efficiency as a function of foil thickness for gold, uranium and uranium dioxide for 5-MeV alpha-particles, L_i is the intercept of linear fitting curve on x-axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is constant (0.25), and the applicable range of L within the linear scope of fitting curve is around [0, $1/2L_i$].

4. Calculation of propulsion

In this section, the force generated by the NcPP sail was calculated, which is a foil of decayable material of several microns. With the predicted propulsion force and the total mass of the spacecraft, the acceleration of the NcPP sail can be obtained. From the acceleration, one can estimate the final velocity available for the NcPP sail. The mass loss effect during the decay is considered negligible (see Supplementary Materials S4).

In this study, ^{232}U, ^{238}Pu, and their dioxides were chosen as the foil materials, because these synthetic isotopes possess moderately long half-lives of 68.9 and 87.7 years, respectively (Audi et al., 2003). The decay chains of these two isotopes (Lederer et al., 1968; Pritychenko et al., 2014; Evaluated nuclear structure data file (ENSDF), 1992) are shown in Fig. 3.

For ^{232}U, the decay series emit six alpha particles and the half-lives for the later five alpha decays are much less than 68.9 years. Therefore, the emission of alpha particles can be considered as an immediate continuation of the first decay step, and the propulsion pressure of ^{232}U can be estimated as six times of that for materials with a single alpha particle emission. For ^{238}Pu, the alpha decay in the second or third step has an extremely long half-life, and hence the following emitted alpha particles can be neglected. Considering the multi-emission effects of alpha particles, the formula for multiply propulsion pressure is (see Supplementary Materials S2).

$$Pr_m = \frac{\ln\ 2}{T_{1/2}} 0.5^{\frac{t}{T_{1/2}}} \frac{n\bar{P}L\overline{\eta_P}\rho N_A\chi}{M'}, , \tag{2}$$

where L, ρ, N_A, χ, and M' are the thickness, mass density of decayable material, Avogadro's number, purity of the decayable isotopes, and the relative atomic mass of the compounds, respectively, $T_{1/2}$ is half-life, $\bar{P}$ and $\overline{\eta_P}$ indicate the average momentum and efficiency of emitted particles, and n is the number of alpha particle emissions in a multistep decay reaction, that is, the emission number.

The densities of pure uranium and plutonium are approximately 19 g/cm^3, (CRC handbook of chemistry and physics, 2014) and those of their dioxides are approximately 11 g/cm^3 (Sutton and Osor, 2010, http://www.webelements.com/). Assuming time t"$T_{1/2}$, setting all emitting particles with energy 5 MeV and χ=1, and substituting into Eq. (2), we obtain the propulsion pressure as a function of foil thickness (Fig. 4A). The propulsion pressure can reach 8 μN/m^2 for pure ^{232}U and approximately 1 μN/m^2 for ^{238}Pu. These values are in the same order of magnitude with that for the solar sails, which is approximately 9 μN/m^2 when the sail is near the Earth in space (Wright, 1992). In short, the propulsion generated by alpha decay foils is significant.

Because the propulsion force and the total mass increase simultaneously with the increasing foil thickness and larger mass may result in lower acceleration, the optimal value of the foil thickness to get the maximum acceleration or speed should be determined. When setting the m_{load} as the mass of the spacecraft including the absorption layers and γ as the ratio of the m_{load} to the fuel mass, the formulas for optimal acceleration and optimally increased velocity of the spacecraft are (see Supplementary Materials S3).

$$a_{opt} = \frac{\ln\ 2}{4T_{1/2}} 0.5^{\frac{t}{T_{1/2}}} \frac{n\bar{P}N_A\chi}{M'(1+2\gamma)} \tag{3}$$

and.

$$\Delta V = \int_{t_0}^{t_f} a_{opt}\,dt = \frac{1}{4}\frac{n\bar{P}N_A\chi}{M'(2\gamma+1)}\left(0.5^{\frac{t_0}{T_{1/2}}} - 0.5^{\frac{t_f}{T_{1/2}}}\right), \tag{4}$$

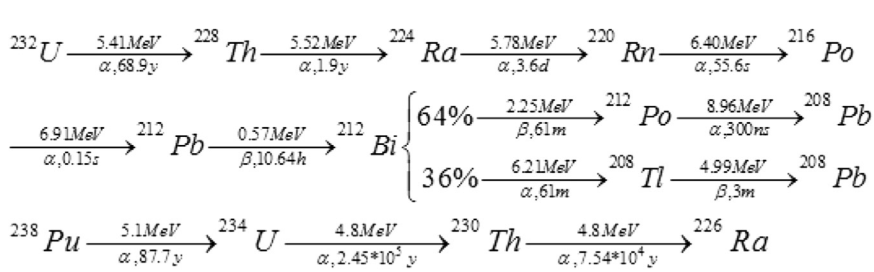

Fig. 3. The decay chains of U-232 and Pu-238. The numbers above arrows are the energies of alpha-particles and those below are the decay types and half-life times.

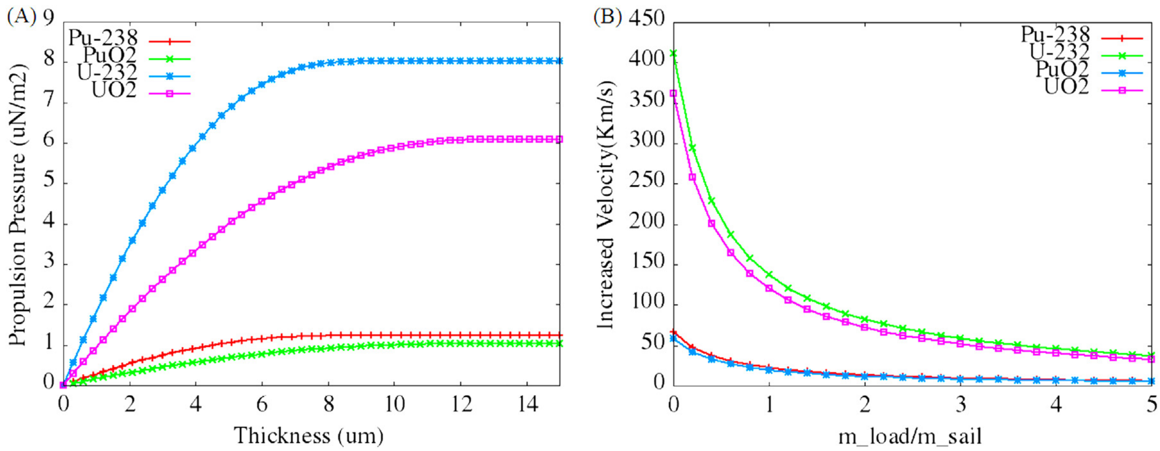

Fig. 4. (A) The propulsion pressure as a function of thickness; (B) The influence of ratio between the load mass and the fuel mass on the increased velocity.

respectively, where t_0 and t_f are the initial and final times for the integral.

From Eq. (4), it can be found that the increased velocity only depends on emission number n, momentum P, atomic mass M' and mass ratio γ at given χ, t_0, and t_f. The first three parameters are determined by the decayable material. The mass ratio γ has a significant effect on the maximum velocity. When setting $\chi=1$, $t_0=0$, and $t_f=\infty$, the increased velocity as a function of mass ratio γ is shown in Fig. 4B. If light-weighted absorption layer can be found, and the load is low with $\gamma=0.2$, the increased velocity of ^{232}U and ^{238}Pu can reach approximately 300 and 50 km/s, respectively. When the more practical value of $\gamma=1$ is used, the increased velocity could be approximately 140 and 20 km/s. The results show an excellent agreement with Bolonkin's results (Bolonkin, 2005). It can also be seen that the acceleration effect of metals is better than that of the dioxide.

5. Comparison of NcPP sails and solar sails

The solar sail is based on the solar radiation-generated photon pressure, which is proportional to the intensity of sunshine (Wright, 1992). In 2010, the Japan-made solar sail spacecraft IKAROS was launched into space to travel to Venus (Small, 2010). It is interesting to compare the NcPP sails with the solar sails.

For space travel calculations, let us ignore the influence of gravities of planets and suppose that the travel trajectory is directly away from the Sun and the distances to planets' orbits are estimated by the semi major axis. Because the solar pressure is inversely proportional to the square of the distance from the Sun (D), the pressure can be estimated as follows:

$$Pr_{solar} = Pr_{Earth}\frac{D^2_{Earth}}{D^2}, \tag{5}$$

where Pr_{Earth} and D_{Earth} are the solar pressure at the Earth and the distance between the Sun and the Earth.

For a spacecraft with a load of 50 kg and a load–fuel ratio of 1 ($\gamma=1.0$), 50 kg of fuel is needed. When choosing pure metal as the NcPP sail material, the optimal thickness of the sail is 6 μm and the sail area is 463 m^2, for panel with diameter 24.3 m. We then compare it with the solar sail with the same thickness and mass. Let us assume the material of the solar sail to be aluminum with density 2.7 g/cm^3 and the area of the solar sail 3087 m^2. Another assumption adopted for the predictions is that acceleration starts from the Earth with an initial velocity of 16 km/s.

Table, 1 shows the time needed to travel to Mars, Saturn, Pluto, and Proxima Centauri with load–fuel ratios γ of 1.0 and 0.2. For a short-distance travel, the natural decay based on NcPP sails does not possess obvious advantages compared with other propulsion technologies, because of their long half-lives. However, for a long-distance travel, the advantages of the NcPP sails are notable. It can reduce the travel time to Proxima Centauri to 11% of that under the current technologies, approximately a nine times improvement. At load–fuel ratio γ of 0.2, the final velocity for the ^{232}U NcPP sail can reach 300 km/s, near 1/1000 of the light speed. However, a travel to Proxima Centauri still takes thousands of years. Interstellar travel definitely asks for even better propulsion technologies.

Table 1 The time needed to travel to Mars, Saturn, Pluto, and Proxima Centauri with three types of space propulsion sails. The numbers in bracket are the needed time ratio between the sail and a spacecraft with a constant speed of 16 km/s.

Destination	Travel time (year) Condition: Initial Speed = 16 km/s			
	No Sail (16 km/s)	Solar Sail ($\gamma=1$)	^{232}U NcPP ($\gamma=1$)	^{232}U NcPP ($\gamma=0.2$)
Mars	0.456 (1.00)	0.416 (0.91)	0.438 (0.96)	0.432 (0.95)
Saturn	2.540 (1.00)	2.192 (0.86)	2.310 (0.91)	2.13 (0.84)
Pluto	11.4 (1.00)	9.55 (0.84)	8.42 (0.73)	6.98 (0.61)
Proxima Centauri	79,000 (1.00)	66,000 (0.83)	8700 (0.11)	4300 (0.06)

6. Hypothesis of SAND

For less-ambitious goals, the NcPP sails can be used for position and gesture maneuvering in space. It can be reliably used in satellites and space stations for many years. For the ambitious goal of leaving our solar system, a new mechanism of propulsion is needed.

According to Eq. (2), the half-life has a significant effect on the propulsion pressure. Shorter half-lives could lead to higher propulsion, which indicates that higher acceleration can be achieved if half-life is artificially modulated. Ideally, the NcPP sail material should have a stable state and excited state. In the stable state, it has a very long half-life, exhibiting little propulsion, whereas in the excited state, its half-life can be extremely shortened by an external energy field. In this way, the NcPP material can release almost all of its Nc-particles immediately and generate a huge propulsion force. This turns the NcPP materials into much more convenient fuels, such as gasoline, which release their energy only upon ignition.

For example, with a half-life $<$ 1d, the ^{232}U film (thickness 6 μ) can generate a propulsion pressure of approximately 0.15 N/m^2.

With such high propulsion force, a velocity as high as 150 km/s could be achieved in several days, and the trip to Mars could be completed within 20 days.

Natural nuclear decay is relatively stable under normal energy fields. However, when ultra-intense laser radiation is used, nuclear energy levels can be excited and the half-life time constant could be modified, (Ledingham et al., 2003) which indicates that laser SAND (laser-stimulated acceleration of nuclear decay) may be a potential solution for our hypothesis. Some studies have been conducted using ultra-intense lasers in nuclear waste treatment revealing the feasibility of SAND (Bounds and Dyer, 1992; Schwoerer et al., 2001; Belyaev et al., 2005). In general, new schemes, including novel designs of laser or decay materials, might be the accessible solutions. Engineering feasible systems for space exploration awaits future exploration.

Acknowledgments

The authors thank Prof. X.P. Ouyang (Northwest Institute of Nuclear Technology, Shanxi 710000, China), Prof. Q.B. Ren (Xi'an Aerospace Propulsion Institute, Shanxi 710000, China), and Prof. Qing Huang (Specialty Fibers and Nuclear Materials Engineering Laboratory, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Zhejiang 315201, China) for their useful discussions.

The authors acknowledge the support from the team of Laser and Intelligent Energy Field Manufacturing. This study was supported by the Chinese Academy of Sciences (CAS) and the Key Technology of Nuclear Energy, 2014, CAS Interdisciplinary Innovation Team and ITaP at Purdue University, Indiana, USA, for computing resources.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.apradiso.2016.04.005.

References

Audi, G., Bersillon, O., Blachot, J., Wapstra, A.H., 2003. The NUBASE evaluation of nuclear and decay properties. Nucl. Phys. A 729 (1), 3–128.
Berman, A.I., 1961. Physical Principles of Aeronautics. Wiley, New York, pp. 252–254.
Bolonkin, A.A., 1982. Radioisotope propulsion. Russ. Pat. Appl. 3467762 (25), 116952.
Bolonkin, A.A, 2005. Radioisotope Space Sail and Electro-Generator. 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, pp. 1–7.
Bennett, G.L., Lombardo, J.J., Hemler, R.J., et al., 2008. The general-purpose heat source radio isotope thermo electric generator: a truly general-purpose space RTG. Space Technol. Appl. Int. Forum 969 (1), 663–671.
Bethe, H.A., 1953. Moliere's theory of multiple scattering. Phys. Rev. 89, 1256–1266.
Boschini, M.J., Consolandi, C., Gervasi, M., et al., 2010, Nuclear and non-ionizing energy-loss for coulomb scattered particles from low energy up to relativistic regime in space radiation environment, Proc. 12th ICATPP Conf.
Bounds, J.A., Dyer, P., 1992. Search for nuclear excitation by laser-driven electron motion. Phys. Rev. C 46 (3), 852.
Belyaev, V.S., Matafonov, A.P., Vinogradov, V.I., et al., 2005. Observation of neutronless fusion reactions in picosecond laser plasmas. Phys. Rev. E 72 (2), 026406.
Cassady, L.D., Longmier, B.W., Olsen, C.S., et al., 2010. VASIMR Performance Results, 46th Jt. Propuls. Conf.
Colombo, C., Vasile, M., Radice, G., 2009. Optimal low-thrust trajectories to asteroids through an algorithm based on differential dynamic programming. Celest. Mech. Dyn. Astron. 105 (1), 75–112.
Comfort, J.R., Decker, J.F., Lynk, E.T., Scully, M.O., Quinton, A.R., 1966. Energy loss and straggling of alpha particles in metal foils. Phys. Rev. 150, 249–257.
CRC Handbook of Chemistry and Physics, 2014. CRC press.
Evaluated nuclear structure data file (ENSDF), 1992. Springer Berlin Heidelberg.
Fiehler, D., Oleson, S., 2005. Radioisotope electric propulsion missions utilizing a common space- crafe design. Acta Astro. 57, 444–454.
Gravier, J.P., Marchal, C., Culp, R.D., 1972. Optimal trajectories between Earth and Mars in their true planetary orbits. J. Optim. Theory Appl. 9 (2), 120–136.
Harwood, W, 2006. New Horizons Launches on Voyage to Pluto and Beyond, ⟨http://spaceflightnow.com/atlas/av010/060119launch.html⟩.
⟨http://www.webelements.com/⟩.
Kluever, C.A., 1997. Optimal low-thrust interplanetary trajectories by direct method techniques. J. Astro. Sci. 45 (3), 247–262.
Longmier, B.W., Squire, J.P., Olsen, C.S., et al., 2012. VASIMR VX-200 Improved Throttling Range. 48th Joint Propuls. Conf.
Loveland, W.D., Morrissey, D.J., Seaborg, G.T., 2005. Modern Nuclear Chemistry. Wiley, New York, pp. 177–179.
Lederer, C.M., Hollander, J.M., Perlman, I., 1968. Table of Isotopes. Wiley.
Ledingham, K.W.D., McKenna, P., Singhal, R.P., 2003. Applications for Nuclear Phenomena generatedby ultra-intense lasers. Science 300 (5622), 1107–1111.
Pritychenko, B., Běták, E., Singh, B., et al., 2014. Nuclear science references database. Nucl. Data Sheets 120, 291–293.
Sutton, G.P., Oscar, B., 2010. Rocket Propulsion Elements (ed.). 7. Wiley, New York, pp. 102–106.
Solar Small Power Sail Demonstrator'IKAROS' Successful Attitude Control by Liquid Crystal Device. (JAXA, 23.07.10). ⟨http://global.jaxa.jp/press/2010/07/20100723_ikaros_e.html⟩.
Schwoerer, H., Gibbon, P., Düsterer, S., et al., 2001. MeV X rays and photoneutrons from Femtosecond laser-produced plasmas. Phys. Rev. Lett. 86 (11), 2317.
Wright, J.L., 1992. Space Sailing. Taylor & Francis, pp. 1–8.
Ziegler, J.F., Ziegler, M.D., Biersack, J.P., 2010. SRIM–The stopping and range of ions in matter. Nucl. Instrum. Methods Phys. Res. Sect. B: Beam Interact. Mater. At. 268 (11), 1818–1823.